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REPORT

**An appraisal of the use of
holographic techniques in television
systems of broadcast quality**

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**AN APPRAISAL OF THE USE OF HOLOGRAPHIC TECHNIQUES IN
TELEVISION SYSTEMS OF BROADCAST QUALITY**
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Summary

Brief accounts are given of the theoretical and practical aspects of the preparation of a hologram, and the occurrence of the speckle pattern. The use of holographic techniques in a television transmission system is examined in detail, and it is concluded that it does not appear feasible to develop such a system.

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FOREWORD

The material presented in Sections 1 and 2 of this Report repeats in abbreviated form the subject-matter of Report 1973/38 (Holography: A General Survey). It is here included for the sake of completeness and to avoid the necessity of making extensive cross-references between the two Reports.

AN APPRAISAL OF THE USE OF HOLOGRAPHIC TECHNIQUES IN TELEVISION SYSTEMS OF BROADCAST QUALITY

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1. Introduction

Holographic techniques have been described in detail elsewhere.^{1,2,3} Briefly, a hologram consists of a recording, on photographic film or other suitable light-sensitive material, of part of the interference pattern formed in the common volume occupied by two distinct components of coherent radiation, initially derived from the same source (usually a laser^{4,5}). The distinction between these two components of radiation lies in the paths traversed in each case. The path of one component (the 'object beam') includes reflection from (or transmission through) the object whose image is to be stored holographically. The other component (the 'reference beam') has a well-defined path whose geometry can be readily duplicated. When the hologram is illuminated by a 'reconstruction beam' of radiation having the same wavelength and geometry as that of the original reference beam, diffraction occurs from the grating-like structure formed by the recording of the interference pattern. One of the diffracted components is a reconstruction of the original wave-front issuing from the object, giving rise to a 'reconstructed' image of the original object occupying the same position in space (relative to the plate) as the original object. The other diffracted component is the so-called 'twin wave', giving rise to an image occupying the alternative position of the object which would have produced the same recorded diffraction pattern.

If the radiation from the object has diffuse properties, either by virtue of the introduction of a diffusing surface into the object illuminating beam, or because of diffuse scattering of the illumination by an opaque object, light from any one part of the object will be spread over the entire area of the hologram: thus any portion of the hologram will contain information concerning the entire object and a complete image can be reconstructed from it. This means that the whole reconstructed image can be viewed from a variety of directions without optical aids, and that the image of a three-dimensional object will also be three-dimensional and give the appearance of observing the original object through a window formed by the hologram itself. In making such a so-called 'diffuse' hologram, laser radiation of adequately long 'coherence length' is required. By 'coherence length' is meant the greatest distance between two points along the direction of propagation of the radiation such that significant correlation exists between the phase of the radiation at each point. This distance is equal to the greatest difference in path length in the two arms of an interferometer for which, when using the radiation under consideration, distinct interference fringes are produced: it is related to the degree of monochromaticity of the radiation.^{2a,3a} This consideration is discussed in Section 3.3.4.

A disadvantage in the use of diffuse coherent illumination is the appearance of the so-called 'speckle pattern', a fine random granular pattern produced by mutual inter-

ference between components of reflected light emanating from the different elementary portions of the surface. When making a hologram of an object, the granular structure of the speckle pattern will be recorded on the holographic medium in addition to the wanted holographic interference pattern. On reconstructing the holographic image, some of the reconstructing light beam is diffracted away from the straight-through direction because of the presence of this recorded random pattern, to form a 'flare' component. The angular extent of this flare component depends on the 'scale' of the recorded speckle pattern (i.e. the average distance between similar features); this in turn depends on the angle subtended by the object at the hologram, the speckle pattern becoming coarser as the size of the object is reduced. It can be shown^{2b} that the angular extent of the flare components is up to twice the angle subtended by the object at the hologram (this is also shown in Fig. 5). In the limit, if the angular extent of the object is zero, (i.e. if the object is simply a point source), then no speckle-pattern component is produced and no scattering of the reconstructing light beam occurs from this cause. A method of reducing the angular extent of the flare component in a hologram of an extended diffuse object, based on this fact, has been suggested.⁶ In this method, the effective size of the object is reduced, as far as the production of speckle pattern is concerned, by illuminating it with a small patch of coherent light which is scanned over the whole object during the holographic exposure. Another method of eliminating the effect of speckle pattern is the use of a 'heterodyne' system^{1,7,8,9} in which the frequency of the radiation in the reference beam differs from that in the object-illuminating beam. A moving interference pattern is produced, which cannot be recorded on materials such as photographic emulsions: however, by using a suitable method of photoelectric reception, an electrical signal will be produced, consisting of a 'carrier' component having a frequency equal to the frequency difference between the object-illuminating and reference-beam components of the incident radiation, and other 'sideband' components which convey object information.* This signal is made to modulate the intensity of a spot of light which is suitably scanned over a sheet of light-sensitive material. The resulting hologram does not contain the speckle-pattern component. The advantage of eliminating the speckle-pattern component is further discussed in Section 3.3.2.

2. Elementary theory

The theoretical treatment given below serves to illustrate the important features in the production of a hologram and the formation of the reconstructed image. A

* The original spatial carrier frequency (see Section 2) is reduced to zero by using an 'on-axis' reference beam.

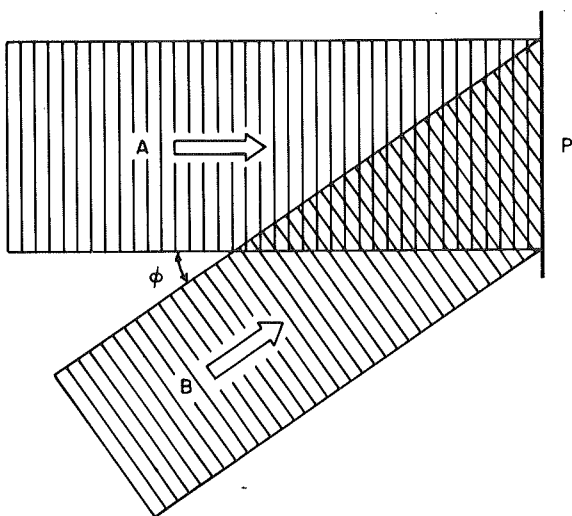


Fig. 1 - Two interfering beams

fuller account of the theory is given elsewhere.^{1,2} Consider two collimated beams (A and B) of monochromatic and mutually coherent light travelling horizontally (and therefore containing vertical plane wave-fronts) and falling on the same area of a vertical flat photographic plate P (Fig. 1). For simplicity, one beam is assumed to be normally incident on to the plate while the angle of incidence of the other beam in a horizontal plane is ϕ . It can be shown that

$$l = \frac{\lambda}{\sin \phi} \quad (1)$$

where l is the spacing of the fringes on the photographic plate. When processed, the plate will carry a series of alternately clear and opaque parallel stripes having the spacing l , and will therefore behave as a diffraction grating. If illuminated by the beam A in Fig. 1, a number of beams

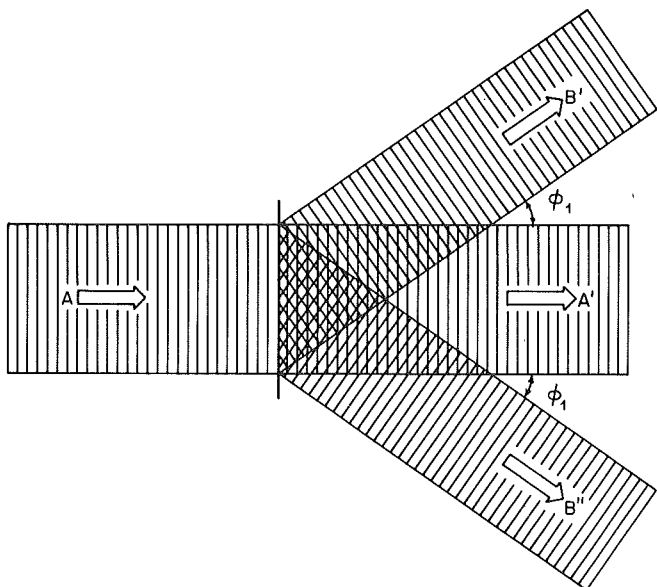


Fig. 2 - Diffraction from two-dimensional recording

will emerge from the plate (Fig. 2) travelling at angles ϕ_n to the normal to the plate, where^{10a}

$$\sin \phi_n = \pm n\lambda/l \quad (n = 0, 1, 2, \dots)$$

Since $\phi_0 = 0$, the condition $n = 0$ corresponds to the 'zero order' or undeviated beam (A' in Fig. 2). The 'first order' ($n = 1$) diffracted beams B' and B'' emerge at angles $\pm\phi_1$, where

$$\sin \phi_1 = \lambda/l \quad (2)$$

Comparing Equations (1) and (2) it can be seen that $\phi_1 = \phi$, and that the beam B' is therefore travelling in the same direction as the original beam B in Fig. 1. The beam B' may therefore be regarded as a 'reconstruction' of the beam B. The beam B'' corresponds to the unwanted 'twin wave' (see Section 1). It may be regarded as the reconstruction of a hypothetical beam incident on to the plate at the same angle as the beam B in Fig. 1, but on the opposite side of beam A', as this hypothetical case would give rise to the same interference pattern, and therefore the same stripe pattern on the processed plate, as in the case discussed above.

If several 'object' beams are simultaneously incident at various angles onto the plate, in addition to the 'reference' beam A, interference patterns will be formed between each such beam and the reference beam. On illuminating the processed plate, reconstructions of each such beam will be produced, together with the respective 'twin waves'. This concept leads to a theoretical treatment^{1,2,11} in which the interference pattern produced by an extended object and recorded on the hologram may be regarded as being composed of a number of Fourier components. Each such component constitutes an elementary grating and diffracts light into two first-order components. The superimposition of the components from all the elementary gratings gives the total radiation field diffracted by the hologram and it can be shown that this field consists of a reconstruction of the original object wave, together with a conjugate twin wave. A plane wave arriving at the photographic plate along the direction of propagation of the reference wave, and another arriving along a direction related to the position of the object (this direction could, for example, be along the line joining the centre of the object to the centre of the photographic plate), would give rise to a hologram (as described above) consisting of an elementary diffraction grating with a certain periodicity. This periodicity may be regarded as a spatial 'carrier', and all the other Fourier components of the recorded diffraction pattern then become 'sidebands' carrying information about the characteristics of the object and the reference beam.

So far, the description of the holographic process has assumed a process of diffraction from a grating consisting of areas of differing optical transmission. Diffraction will also occur, however, if the phase of the incident radiation is modified^{2c} by the hologram. In the present context, the principal advantage in the use of such a 'phase hologram' instead of the 'amplitude hologram' previously described is that it greatly increases the 'diffraction efficiency' of the system (i.e. the proportion of the radiant energy incident on to the hologram during image reconstruction that it utilised in the wanted image-forming diffracted component).^{2d,12,13,14,15,16}

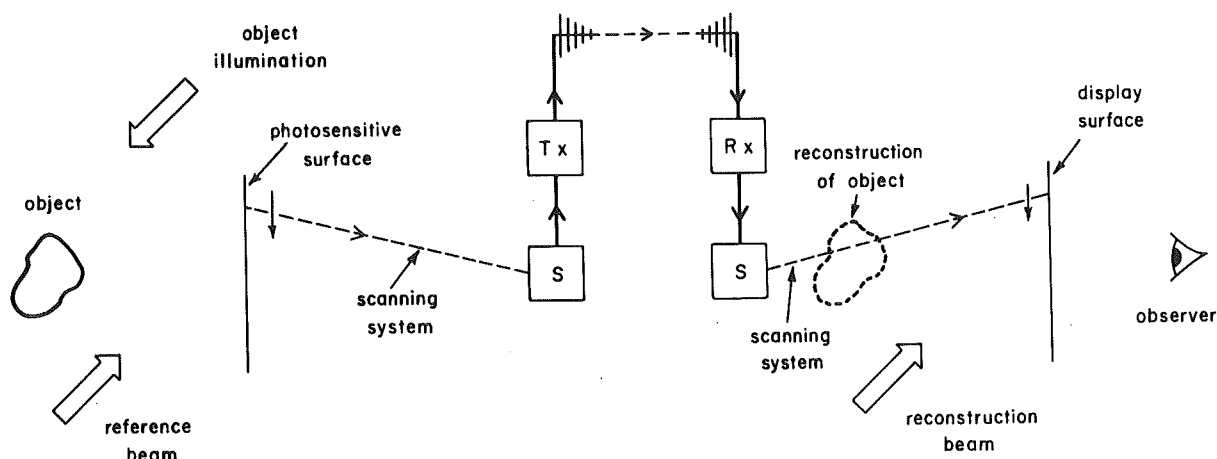


Fig. 3 - Basic holographic television transmission system

3. Holographic television transmission systems

3.1. Basic principles

The ability of a hologram to present a truly three-dimensional image has excited much interest, since in principle a holographic system of television transmission could provide such a display. The basic elements of such a system are shown in Fig. 3. Two beams of coherent light are derived from a single source using a beam-splitting system (not shown) and are used as object illumination and reference beams in a holographic system. A photosensitive surface intercepts the holographic interference pattern, the resulting intensity variations over the surface being converted into a time-varying electrical signal by a scanning system. This signal is suitably processed and radiated by a transmitter. At a receiver, the signal is supplied by way of another scanning system to a 'display' surface, having the property that the relative phase of the light transmitted through (or reflected by) a small area of the surface, or alternatively the optical transmission of the small area, is related to the magnitude of the electrical signal supplied to the surface by the scanning system. A phase or amplitude hologram is thus built up on the surface, which when illuminated by a suitable reconstruction beam will provide a holographic image of the original object.

Although simple in principle, many practical difficulties prevent the easy implementation of such a transmission system. The principal difficulties are:—

- (a) Because of the very fine structure of the holographic interference pattern, a very high bandwidth would be required to transmit the electrical signal resulting from the scanning process, remembering that a rapid succession of holograms would be required to preserve the illusion of object motion.
- (b) The quality of the received image would be impaired by flare and speckle-pattern effects, and difficulties would occur if image reconstruction in colour was to be attempted.
- (c) Some of the elements of the holographic system

shown in Fig. 3 do not at present exist in a form suitable for use in a broadcasting system.

- (d) Severe restrictions would be placed on the nature of the scene material capable of being transmitted.

These difficulties are discussed in Sections 3.2 and 3.3, being summarised in Section 3.3.4 with particular reference to the use of a holographic transmission system for public-service broadcasting.

3.2. Considerations of bandwidth

An estimate of the order of magnitude of the bandwidth required in the basic holographic television transmission system shown in Fig. 3 may be obtained by investing certain parameters of the system with arbitrary but 'reasonable' values. Consider the case in which:

- (a) The wavelength of the coherent light is 632.8 nm (He-Ne laser radiation).
- (b) The dimensions of the photosensitive surface and the display surface are 40 cm (horizontal) and 30 cm (vertical).
- (c) The reference beam angle is 30° , the beam being collimated and travelling horizontally, and originating on the left-hand side of the object.*
- (d) The object consists of a sphere subtending an angle of 18° at the photosensitive surface, the object being centrally disposed relative to the photosensitive surface.**
- (e) Sequential scanning is used, the scanning lines being horizontal. One complete scan occupies 20 ms.

* Throughout this section 'left' and 'right' refer to the view of the observer looking towards the virtual source of the reference or reconstruction beam.

** An object of height 62 cm (say two feet) placed 205 cm (say seven feet) from the photosensitive surface would subtend this angle: the reconstructed image would occupy the full height of the display at a viewing distance of six times the picture height.

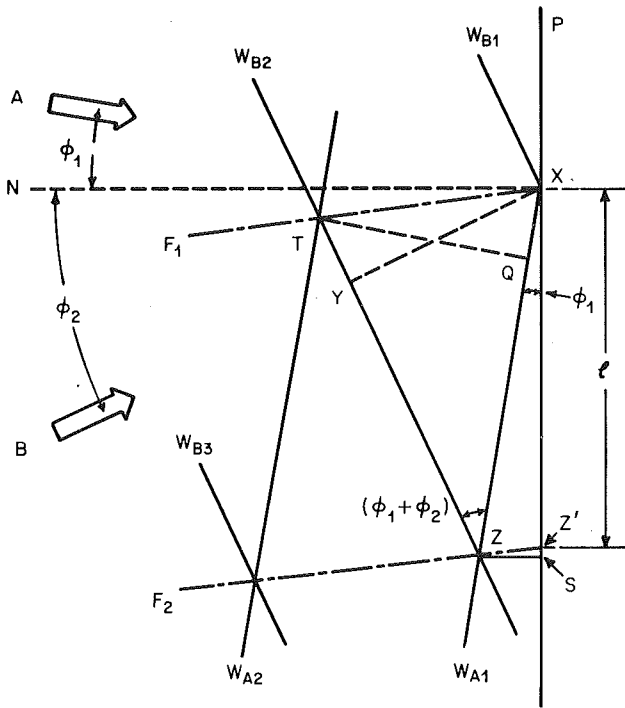


Fig. 4 - Geometry of two non-normal interfering beams: two-dimensional case

The overall interference pattern laid down on the photosensitive surface can be described in terms of the 'spatial spectra' (i.e. the distribution of spatial frequencies) in the vertical and horizontal direction. These spatial spectra may be derived by first considering two collimated beams A and B, of wavelength λ , arriving at angles of incidence to the photosensitive surface of ϕ_1 and ϕ_2 respectively (Fig. 4). The convention is adopted that the beams arrive on opposite sides of the normal XN to the photosensitive surface P and that ϕ_1 is smaller than ϕ_2 ; ϕ_1 becomes negative in the case in which both beams are on the same side of XN. The beams A and B contain plane wavefronts W_{A1}, W_{A2}, \dots and W_{B1}, W_{B2}, \dots , corresponding features of the interference fringes being formed in planes F_1, F_2, \dots . The two sets of wavefronts meet at an angle $(\phi_1 + \phi_2)$; hence in the right-angled triangles XYZ and TQZ

$$\angle XZY = \angle TQZ = \phi_1 + \phi_2$$

It can be shown¹ that

$$XZ = TZ = \frac{\lambda}{\sin(\phi_1 + \phi_2)} = k, \text{ say} \quad (3)$$

Hence in the isosceles triangle TZX,

$$\angle XTZ = 90^\circ - \frac{(\phi_1 + \phi_2)}{2}$$

and therefore, in the right-angled triangle TYX,

$$\angle TXY = \frac{\phi_1 + \phi_2}{2}$$

Since $\angle XNY = \phi_2$,

$$\angle XNT = \frac{\phi_2 - \phi_1}{2}$$

The fringe planes F_1, F_2, \dots therefore make an angle $(\phi_2 - \phi_1)/2$ with the normal XN to the photosensitive surface. Planes F_1 and F_2 intercept the photosensitive surface at X and Z' , the length XZ' ($= l$) giving the distance between successive fringes in the holographic pattern. It can be seen that

$$l = XS - SZ' \quad (4)$$

In the right-angled triangle XSZ,

$$\angle SZX = \phi_1$$

hence

$$XS = k \cos \phi_1$$

Furthermore, in the right-angled triangle SZS',

$$\angle Z'SZ = \frac{\phi_2 - \phi_1}{2}$$

hence

$$SZ' = k \sin \phi_1 \tan \left(\frac{\phi_2 - \phi_1}{2} \right)$$

and from Equation (4)

$$\begin{aligned} l &= k \left[\cos \phi_1 - \sin \phi_1 \tan \left(\frac{\phi_2 - \phi_1}{2} \right) \right] \\ &= k \left[\frac{1 + \cos(\phi_1 + \phi_2)}{\cos \phi_1 + \cos \phi_2} \right] \end{aligned} \quad (5)$$

hence from Equation (3)

$$l = \lambda \cdot \frac{1 + \cos(\phi_1 + \phi_2)}{\sin(\phi_1 + \phi_2)(\cos \phi_1 + \cos \phi_2)} \quad (6)$$

The spatial frequency of the interference pattern (n) is therefore given by

$$n = \frac{\sin(\phi_1 + \phi_2)(\cos \phi_1 + \cos \phi_2)}{\lambda[1 + \cos(\phi_1 + \phi_2)]} \times 10^6 \quad (7)$$

where λ is expressed in nm

and n is expressed in cycles/mm

TABLE 1

Spatial Frequencies

Item	Origin of ray pairs ('Extremities' of object or image are as seen by observer)	ϕ_1	ϕ_2	n (cycles per mm)	p (Equation 8)
1	Two diametrically opposite points at extreme edges of object	9°	9°	494	27.4
2	Reference beam and centre of object	0°	30°	790	26.3
3	Reference beam and extreme left-hand side of object	-9°	30°	543	25.9
4	Reference beam and extreme right-hand side of object	9°	30°	1037	26.6
5	Reference beam and extreme top of object (ϕ_1 and ϕ_2 not in same plane)	9°	30°	830	$\bar{p} = 26.6$

Equation (7) may now be used to calculate some spatial frequency components of the overall interference pattern.* Table 1 shows values for ϕ_1 and ϕ_2 (see Fig. 4) for pairs of rays which contribute to the interference pattern, and the corresponding spatial frequencies produced by each of these ray pairs. Item 1 represents the highest spatial frequency present in the speckle pattern component due to self-interference of light from the object (see Section 1). The speckle pattern therefore contains frequencies extending from zero up to this maximum value. This is shown diagrammatically in Fig. 5, in which the vector length from the origin represents the magnitude of

* This aspect is discussed in more general terms by Macovski.¹⁷

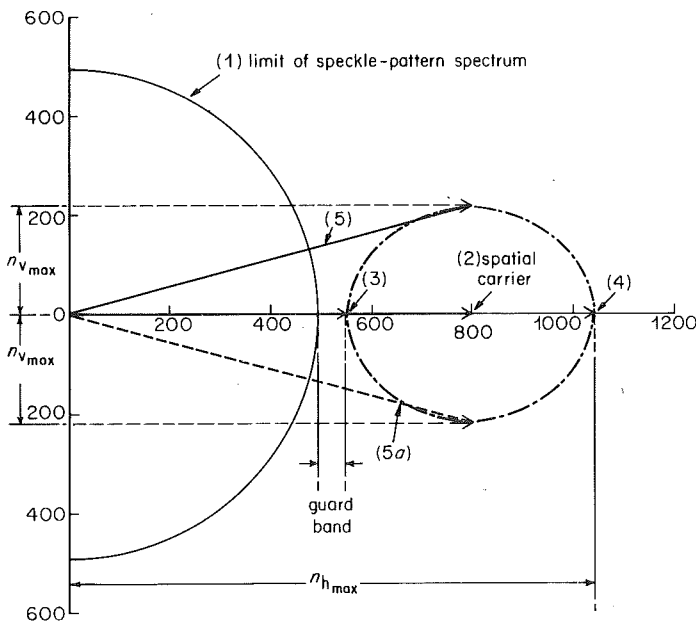


Fig. 5 - Spatial-frequency spectrum for basic holographic system

Numbers in brackets refer to the corresponding items in Table 1

the spatial frequency, and the vector orientation the 'direction' of the spatial frequency (i.e. the direction of the normal to the set of fringes under consideration).* The shape of the speckle-pattern spectrum (a semi-circle in the present case) is dictated by the shape of the object.

For the reconstructed image to be free of flare light due to the recorded speckle-pattern component, the spatial frequencies involved in the holographic interference pattern must all be higher than any of the speckle-pattern components.^{2b,8,11,18} This situation is achieved by a suitable choice of object dimensions and reference-beam angle. In the present case the angular relationships between the reference beam and rays emanating from the centre and horizontal extremities of the object have been chosen so as to occupy the available range of spatial frequency leaving only a small 'guard band' between the speckle-pattern and holographic-pattern components. In Table 1, Item 2 refers to interference between light from the centre of the object and light in the reference beam and therefore gives rise to the 'spatial carrier' component in Fig. 5, while Items 3 and 4 give rise to the lowest- and highest-valued spatial frequency components. It is immediately apparent that the values of spatial frequency are about three orders of magnitude higher than those involved in present-day television displays. The interference patterns produced in these three cases all consist of vertical bar patterns, and the corresponding spatial frequencies are therefore represented as lying on the horizontal axis in Fig. 5.

The situation produced by the conditions of Item 5 in Table 1 will give rise to a bar pattern inclined to the vertical. The simple two-dimensional treatment implicit in Fig. 4 and Equation (7) can no longer be used to determine the spatial frequency of this component, since the plane containing the reference-beam direction and the ray from the object, both passing through the point X (Fig. 4) on the

* The two quadrants shown are sufficient to describe all possible spatial frequencies.

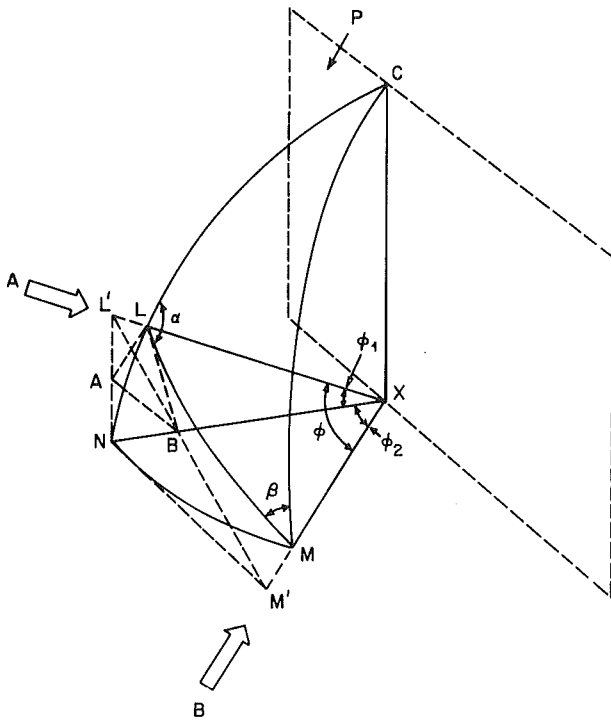


Fig. 6 - Geometry of two non-normal interfering beams: three-dimensional case

photosensitive surface, no longer contains the normal XN to this surface. It may, however, be seen from Table 1 that for the range of angles under consideration the spatial frequency is approximately proportional to the angle $(\phi_1 + \phi_2)$ between the two interfering beams of light, and is virtually independent of the orientation of the photosensitive surface. Equation (7) may therefore be approximately expressed as:

$$n = \bar{p}(\phi_1 + \phi_2) = \bar{p}\phi \quad (8)$$

where \bar{p} is the mean of the values of p given in the right-hand column of Table 1, and ϕ is the angle* between the two interfering beams of light.

In Fig. 6, the plane P represents the photosensitive surface and XN is the normal to this surface through the centre of the object. LX is a ray of light from the extreme top of the object making an angle ϕ_1 with the photosensitive surface; hence $\angle LXN = \phi_1$. MX defines the direction of arrival of the reference beam, so that $\angle MXN = \phi_2$. The angle ϕ between the two beams is thus $\angle LXM$; since NX is not in the plane LXM, $\phi \neq \phi_1 + \phi_2$. CM, CLN and LM are great circles on a sphere of arbitrary radius and centre X. It can be shown¹⁹ that in the spherical triangle CLM,

$$\tan \frac{\alpha - \beta}{2} = \cot \frac{\phi_2}{2} \tan \frac{\phi_1}{2} \quad (9)$$

* Note that $(\phi_1 + \phi_2) = \phi$ only in the two-dimensional case of Fig. 4.

$$\tan \frac{\alpha + \beta}{2} = \cot \frac{\phi_2}{2} \cot \frac{\phi_1}{2} \quad (10)$$

$$\text{and} \quad \tan \frac{\phi}{2} = \tan \frac{\phi_1}{2} \cdot \frac{\sin \frac{\alpha + \beta}{2}}{\sin \frac{\alpha - \beta}{2}} \quad (11)$$

Solving Equations 9 – 11 for the values of ϕ_1 and ϕ_2 given in Item 5 of Table 1,

$$\alpha = 105.2^\circ \quad (12)$$

$$\text{and} \quad \phi = 31.2^\circ \quad (13)$$

From Equation (12)

$$\angle NLM = 180^\circ - \alpha = 74.8^\circ$$

hence in the triangle LAB on the plane tangential to the sphere at L,

$$\angle ALB = 74.8^\circ$$

By considering the right-angled triangles LAB, L'AB (on the plane tangential to the sphere at N and therefore parallel to the plane of the photosensitive surface) and ALL' (on the plane perpendicular to that of the photosensitive surface and containing the normal NX to this surface) it can be shown that

$$\tan \angle L'B = \cos \phi_1 \tan \angle ALB$$

hence

$$\angle L'B = 74.6^\circ$$

and from the right-angled triangle L'M'N in the plane parallel to the photosensitive surface

$$\angle L'M'N = 15.4^\circ$$

Since the fringes due to the interference of light in the rays LX and MX occur in planes perpendicular to the plane containing these two rays, the angle $\angle L'M'N$ represents the inclination to the vertical of the intercepts of these fringes with the photoreceptive surface. The direction of the spatial frequency vector corresponding to this set of fringes (Item 5 in Fig. 5) is therefore at an angle of 15.4° to the horizontal, the magnitude being given by substituting Equation (13) into Equation (8). A vector of the same magnitude but of opposite inclination (Item 5a in Fig. 5) would correspond to the interference pattern produced by light from the extreme bottom of the object.

Table 2 shows the highest spatial frequencies involved in the holographic interference pattern. Vertical components of greater magnitude are present in the speckle-pattern spectrum but these may be disregarded as the accurate reproduction of this pattern is not necessary at the holographic receiver (in fact its presence is undesirable, and methods of suppressing it are described in Section 3.3.2). Considering first the vertical component, the number of lines in the television scanning system must be

TABLE 2

Highest Spatial-Frequency Components in Holographic Interference Pattern

Component	Vector in Figure 5	Magnitude (cycles/mm)	No. of cycles in complete display
Vertical	Vertical component of Items 5 or 5a	220	6.6×10^4
Horizontal	Item 4	1037	4.15×10^5

at least twice the greatest possible number of interference-pattern cycles in the picture height (see Table 2) for correct reproduction of the pattern at the receiver. This leads to the requirement of at least 1.32×10^5 scanning lines. Since a complete field is scanned in 20 ms, each complete line occupies a duration of $0.15 \mu\text{s}$. The bandwidth required to transmit the number of cycles of interference pattern shown in Table 2 is thus 2.8×10^5 MHz. The basic holographic television transmission system shown in Fig. 3 therefore requires a video bandwidth which exceeds the present-day system bandwidth by a factor of approximately 5×10^5 , and thus must be regarded as wholly impracticable to implement in the foreseeable future.

The spectrum of the holographic interference pattern (Items 2 to 5 in Fig. 5) may be considered as a 'carrier' spatial-frequency component (Item 2) and 'modulation' spatial-frequency components extending outwards in all directions from this carrier component. The foregoing analysis shows that the locus of the highest-valued modulation components are approximately circular, as shown by the chain-dashed line in Fig. 5, their magnitude being approximately half that of the highest-valued speckle-pattern components (Item 1 in Fig. 5). This property of the speckle-pattern components has been described by Smith.^{2b}

3.3. Methods of reducing the bandwidth

3.3.1. Reduction of the angular extent of the object

Equation (8) shows that a reduction in the angle subtended by the (spherical) object at the photosensitive surface, together with a corresponding reduction of the reference- and reconstruction-beam angles so as to retain only a narrow 'guard band' between the holographic and speckle-pattern spatial frequency components, will produce a proportional reduction in the maximum values of spatial frequency present in the interference pattern. In the vertical direction this will permit a proportional reduction in the number of scanning lines, and therefore a proportional increase in the duration of one such line; in the horizontal direction a proportional reduction in the number of picture elements per line will occur. Thus the overall reduction in bandwidth is proportional to the square of the reduction in subtended angle, or

$$\frac{B_A}{B_B} = \left(\frac{\phi_A}{\phi_B} \right)^2 \quad (14)$$

where ϕ_A and ϕ_B are two values of angle subtended by the object, and B_A and B_B are the corresponding required bandwidths.

A reduction in object subtended angle (or object size, since the angles involved are small) by a factor of ten would therefore give rise to a bandwidth reduction of 100. In terms of the parameters defined in Section 3.2, reducing the object diameter to about 6.2 cm (2½ inches: roughly the size of a tennis ball) would reduce the required bandwidth to 3×10^4 MHz.

3.3.2. Elimination of the speckle-pattern component and reduction of spatial carrier value

The lowest value of spatial-frequency component present in the holographic interference pattern is (in principle, ignoring the need for a 'guard band') equal to the highest value of spatial frequency in the speckle-pattern spectrum. Inspection of Fig. 5 shows that, if the speckle-pattern component were to be entirely eliminated, the value of the spatial carrier could be reduced, resulting in the reduction of the value of the highest horizontal spatial-frequency component by a factor of two. The line describing the limit of the holographic spatial-frequency components (chain-dashed in Fig. 5) would then be tangential to the vertical axis at the origin. In terms of the parameters defined in Section 3.2, the required bandwidth would be 1.5×10^6 MHz. This result could be achieved by filtering the video signal generated in the basic holographic television system of Fig. 3, followed by a frequency down-conversion such that the lowest-frequency component of the electrical signal corresponding to the holographic pattern (Item 3 in Fig. 5) adopted a relatively low (in principle zero) value. At the receiver the reconstruction-beam angle would have to correspond with the lower frequency-changed value of the spatial carrier (Item 2 in Fig. 5). Alternatively, the generation of the speckle-pattern component could be avoided, (see Section 1) either by the technique of scanning a narrow beam of coherent light over the object,⁶ or by the use of the technique of temporal modulation or heterodyne^{7,8,9} using an on-axis reference beam at the transmitter and a reconstruction-beam angle appropriate to the heterodyne-generated spatial carrier at the receiver.

A further halving of the required bandwidth could be achieved by using an on-axis reference beam of the same frequency as the object-illuminating beam. The value of the spatial carrier would then be zero and the line des-

cribing the spectrum of the holographic interference pattern (Fig. 5) would be a semi-circle centred on the origin and of radius approximately $n_{v\max}$. The fact that this spectrum can be completely represented in Fig. 5 by a semi-circle (see footnote on p.5, col.2) indicates the difficulty arising in the use of such a system: in the image reconstruction process (again using an on-axis reconstruction beam) the wanted image and the 'twin image' (see Sections 1 and 2) would not be separable and degradation of the wanted image by the twin-image diffracted radiation would occur.

3.3.3. Reduction of size of photosensitive and display surfaces

The spectrum of the interference pattern is, within the limits of accuracy involved in the present discussion, uniform over the whole area of the photosensitive surface. A reduction in the height of the photosensitive surface would give rise to a proportional reduction in the number of scanning lines required, while a reduction in the width of the surface would produce a proportional reduction in the scanning velocity. Scaling the linear dimensions of the photosensitive surface (and display) by a factor m , while preserving the same display aspect ratio, will therefore produce a change in bandwidth proportional to m^2 . For example, if the dimensions of the display are chosen as 12 cm x 9 cm (a standard photographic plate size), the value of m (relative to the parameter defined in Section 3.2, Item (b)) is 0.3 and the corresponding bandwidth reduction factor is 0.09: the bandwidth requirement for this reduced display size is therefore 2.7×10^5 MHz, assuming no other changes from the basic transmission system shown in Fig. 3.

3.3.4. Discussion

When assessing new television transmission systems, the picture quality achieved by present-day systems must be taken as a standard of comparison. Any potential improvements in particular aspects of picture quality that may be obtained with the new system must represent a worthwhile gain in the system considered as a whole, and must not be accompanied by reductions in other aspects of picture quality that are currently taken as acceptable. Such considerations enable the distinction to be made between a viable new system of television transmission on the one hand, and an interesting but nevertheless unacceptable 'laboratory curiosity' on the other. In the present case, the improvement in picture quality represented by the addition of three-dimensional information must not be made at the expense of reductions of standards in terms of screen size, portrayal of motion, colour and resolution. The first two of these requirements led to the adoption of a 40 cm x 30 cm screen size and to a picture repetition rate of 50 per second (Items (b) and (e) of Section 3.2). Other practical considerations impose a limit on the angle subtended by the subject of the televised scene at the 'taking' photosensitive surface (one example of this restriction is given in the second footnote on p.3: another example would be that of a six foot high human figure, which could not approach the 'camera' nearer than about 21 feet). In fact, another restriction of the maximum size of scene object exists: the optical path difference between light arriving at the photosensitive surface by way of reflection

from the object and light arriving by way of the reference beam must not exceed the coherence length (see Section 1) of the illuminating radiation. A hologram of a 'head and shoulders' view of a human figure^{3b,20} has been successfully made but it appears that this represents the limit in object size with present-day laser techniques.

The necessary use of coherent radiation in object illumination indicates that a holographic television system would be confined to studio use, and that 'outside broadcast' transmissions would not be possible. Even if suitable object illuminating methods could be devised, coherence length considerations (see above) would preclude the transmission of large-scale outside broadcast events.

In the basic holographic transmission system (Fig. 3) the two components furthest from present-day practicability are the scanned photosensitive surface and the display surface. It is unlikely that the photosensitive surface would resemble a conventional camera tube, as the high capacity of such a large target, together with the extremely wide signal bandwidth, would result in an impractically poor signal-to-noise ratio. If such a surface were to be developed, it would probably take the form of a switched array of very small discrete photoelectric devices: about 5.5×10^{10} ($(1.32 \times 10^5) \times (4.15 \times 10^5)$; see Table 2) such devices would be required. It is similarly difficult to envisage a practical form of scanned display surface, the most likely realisation being a form of deformable surface²¹ in which the deformation is controlled by the incoming video signal.

The bandwidth requirement for the holographic transmission system is determined by the angular extent of the scene to be transmitted. In this respect the holographic system differs from a conventional television system, in which the bandwidth requirement is dictated by the resolution requirements of the displayed picture. A restriction in the bandwidth of the video signal in a holographic system would restrict the horizontal 'field of view' of the displayed picture, but within this restricted field of view objects would appear with full definition. Such considerations point to the possibility of 'trading' field of view for reduced object resolution. For example, it might be feasible²² to transmit a coded video signal, each element of the code representing a 'bar pattern' of defined geometrical extent, spatial frequency and phase, pattern inclination and modulation depth. The number of such codes would need to be chosen to give adequate (by present-day standards) resolution while at the same time permitting some reduction in transmitted signal bandwidth. Alternatively, the use of the space coding technique^{23,24,25} might be feasible, if the generation of a pseudoscopic image^{26,27,28} could be avoided.

The transmission of colour using the holographic system can in principle be carried out by using three (red, green and blue) coherent light sources.* It would be

* It must however be noted that a colour-camera analysis characteristic which samples the reflectance value of a coloured object at three wavelengths only (such as would be obtained by using scene illumination consisting of three spectral lines) is likely to give rise to considerable errors in the reproduction of some colours.²⁹

possible to use a separate photosensitive surface for each colour during transmission, and a separate display surface during reception, in both cases using a set of dichroic mirrors to control the appropriate separation or combination of light. Alternatively, one photosensitive and one display surface could be used: problems would then arise in the separation of the three wanted reconstructed images (one of each colour) from the six unwanted images.^{2f,26,30,31,32,33,34} The best solution in this case would probably be the use of the method proposed by Collier and Pennington,³⁴ in which the three 'colour-separation' holograms would be formed on discrete interleaved areas of the photosensitive surface during transmission, using coloured filters, and the three reconstructing beams would be similarly permitted to fall only on the appropriate areas of the display surface.

The foregoing discussion has assumed that the holographic interference pattern is formed from light scattered from the scene to be transmitted, without the use of a lens system, since the light diffracted from the display surface would in this case generate an undistorted three-dimensional image of the original scene. It would of course be possible to place a lens system between the scene and the photosensitive surface; this could reduce the effective angle subtended by objects in the scene at the photosensitive surface, but would not assist in overcoming the 'coherence lengths' problems discussed earlier in this section. The reconstructed image could similarly be viewed through another lens system. Unfortunately, the three-dimensional 'aerial' image formed by a lens shows considerable dimensional distortion, relative to the original three-dimensional object. In particular, the magnification* parallel to the optical axis is proportional to the square of the magnification perpendicular to this axis. For magnifications less than unity (the usual situation in television imaging applications) this will result in very considerable foreshortening of the three-dimensional image: the principal attribute of the holographic television system (the ability to portray three-dimensional objects) is therefore largely lost. It is difficult to envisage a lens system at the display which will compensate for this image distortion.

One further problem concerned with the use of a holographic television transmission system deserves mentioning. If the above-discussed image distortions could be overcome, the reconstructed image might well take the form of a three-dimensional replica of the original scene, but on a much reduced scale. It is apparent that such scale reduction is acceptable in a conventional television display, as indeed it is in any two-dimensional pictorial representation of a three-dimensional scene. It is, however, by no means obvious that this tolerance to what is, in fact, a deliberate distortion of the displayed image, will be carried over into the situation where the 'three-to-two-dimensional' distortion is removed. The situation may well arise in which a three-dimensional representation of the original scene on a reduced scale represents a worse distortion than the currently acceptable reduced-scale two-dimensional representation.

* the ratio $\frac{\text{magnitude of dimension in image}}{\text{magnitude of corresponding dimension in object}}$

4. Conclusions

The transmission of three-dimensional television images of broadcast quality by means of a holographic system involves a very high-bandwidth video signal (of the order of 3×10^6 MHz), and would thus be totally impracticable in the foreseeable future. Components required for opto-electric conversion (cf. the camera tube in a conventional television system) and electro-optic conversion (cf. the conventional display tube) having this bandwidth do not seem likely to be developed on any useful time-scale. Even if such components were to become available, a difficulty would still exist in the provision of coherent scene lighting, since the difference in the source-to-receptor path lengths corresponding to different parts of the scene must not be greater than the coherence length of the radiation, which is at best of the order of a few metres. Furthermore, transmissions from scenes illuminated by daylight or conventional artificial light would be excluded.

It does not therefore appear feasible to develop a holographic television system.

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